11401

NASA TECHNICAL NOTE

NASA TN D-4553

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NASA TN D-4553

CRITERIA FOR SELECTION OF WIRE INSULATIONS FOR USE IN SPACE APPLICATIONS

by Vernon Krueger

Goddard Space Flight Center
Greenbelt, Md.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1968

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ABSTRACT

The properties of five electrical insulation materials (~~Teflon TFE, Teflon FEP, Specification 44 outer space insulation, Novathene,~~ and ~~modified Rayolin-N)~~ were compared, to provide a guide for selecting wire insulations in spacecraft. Of all the properties considered, the outgassing characteristics, radiation resistance, and weight of the materials were considered most important for space applications. Also considered were the workability of these insulations and the amount of fabrication deterioration that wires and cables using them can withstand.

(author, modified)

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INTRODUCTION

The requirements of an electrical insulation for use in space are in many ways unique, and substantially more demanding than those for use on the ground. The fabrication and ground-testing of a spacecraft system demand physical and electrical excellence in the insulation material. Furthermore, when the materials are to be used in outer space, the design engineer must consider their weight, resistance to radiation, and performance in an ultra-high vacuum. This report is intended as a guide for the selection of wire insulations to be used in spacecraft.

The most important properties of such an insulation are:

Outgassing characteristics
Radiation resistance
Weight
Resistance to cold flow
Resistance to cut-through
Resistance to abrasion
Adhesion to potting compounds
Resistance to wicking during soldering
Temperature characteristics

Numerous insulation materials are manufactured for use in hook-up wire; this report will be confined to those most suited to space environments. Those considered are:

Teflon TFE
Teflon FEP
Specification 44*
Novathene
Rayolin-N*

Teflon TFE (poly-tetrafluoroethylene) and Teflon FEP (Copolymer of tetrafluoroethylene and hexafluoropropene) are trade names for two insulation materials manufactured by the Du Pont Corporation. Novathene and Rayolin-N* are trade names for irradiated, modified, polyolefin (Polyethylene) insulation materials developed by the Raychem Corporation. Specification 44* is the trade name for a radiation-cross-linked polyalkene/polyvinylidene fluoride insulation material developed by the Raychem Corporation.

*Modified version of the primary insulation material for outer-space use.

Two insulation materials commonly used in terrestrial environments, polyvinyl chloride and nylon, are noticeably missing from this list. They have been excluded because of their excessively high outgassing rates in vacuum.

Teflon TFE and Teflon FEP are trade names for specific chemical compounds; hook-up wire insulated with these materials can be procured from many sources with no change in characteristics. But it is important to specify the source of hook-up wire that is to be insulated with irradiated, modified polyolefine, and radiation-cross-linked polyalkene/polyvinylidene fluoride materials.

The Specification 44* insulation is specially manufactured by the Raychem Corporation as a modified version of their standard Specification 44 (radiation cross-linked polyalkene/polyvinylidene fluoride) insulation material in which the polyalkene and polyvinylidene fluoride base materials were both reformulated to improve their power to withstand simultaneous exposure to ultra-high vacuum, elevated temperatures, and ionizing radiation. The Novathene insulation is a compound for which the additives have been specially synthesized by Raychem for use in space. The Rayolin-N* insulation is specially manufactured by Raychem as a modified version of their standard Rayolin-N (irradiated, modified, polyolefin) insulation material in which the flame retardant and antioxidant additives have been omitted.

Polyolefin is a generic term covering a number of chemically similar polymers. In the commercial manufacture of polyolefin insulation materials, four basic types of ingredients are compounded, fabricated, and subsequently irradiated with electrons in the 1- to 2-Mev energy range. These four basic components are (1) the polyolefins themselves, (2) the flame-retardant system, (3) antioxidants for protection of the polymer system at elevated temperatures in air, and (4) an "antirad" or radiation protectant. Each manufacturer of this type of insulation has developed his own patented compound, and each compound has its individual characteristics. These differences do not matter on the earth but are extremely important in space. Novathene and Rayolin-N* are the only irradiated, modified, polyolefin insulation compounds for which there are sufficient test data to determine their usefulness in space applications. This does not mean that these are the only suitable materials, but that others should not be used unless they have been tested and found acceptable.

Most of the tests referenced to Raychem reports were conducted by an independent laboratory (Stanford Research Institute Laboratory); all were conducted according to the specifications of Dr. Henry E. Frankel, Chief, Materials Research and Development Branch, Systems Division, Goddard Space Flight Center. The samples used were AWG #20, 600-v hook-up wire with 19/32 stranding.

OUTGASSING CHARACTERISTICS

To ensure a successful mission, the space vehicle designer must recognize and account for the decrease in external atmospheric pressure at high altitudes. The pressure decreases from about 10^3 mm Hg at the earth's surface to 10^{-6} mm Hg at 200 kilometers (125 miles) and less than 10^{-12} mm Hg beyond 6500 kilometers (4000 miles) altitude (Reference 1).

Sublimation (the escape of molecules from solids) is enhanced by the lack of atmosphere. The impact velocities of molecules escaping from the surface of a material generate pressure on the surface enclosure. At a given temperature this pressure is called the vapor pressure. When the molecules rebound from each other in the enclosure and begin to collide with the parent material, they are said to be condensing. Equilibrium is reached when the rate of molecules escaping equals the rate of those condensing. This cannot occur in space, where sublimation proceeds unreversed, at a rate dependent on temperature and material.

Plasticizers used in certain plastic materials have relatively high vapor pressures, which, in high vacuum (less than 10^{-6} Torr) can cause bulk losses and changes in material characteristics by preferential vaporization of volatile constituents (Reference 2).

In evaluating the weight loss and outgassing performance of an insulation, it is important to consider: the initial and subsequent steady-state weight loss, the total weight loss, and the extent of condensable materials evolved as a function of temperature.

The initial rates of weight loss for Teflon, Specification 44*, Novathene, and Rayolin-N*, respectively, are comparable and almost certainly due to entrapped or occluded materials such as carbon dioxide and water.

Gross weight losses have been reported for Teflon TFE, Specification 44*, and Novathene insulated wires; the results are summarized in Table 1 (References 3 and 4). No comparable data are available for Teflon FEP and Rayolin-N*, but it is anticipated that Teflon FEP would exhibit properties similar to Teflon TFE, while Rayolin-N* would exhibit properties similar to Novathene. The insulation materials discussed in this report show very small (and acceptable) weight losses at temperatures significantly higher than those normally encountered in space vehicles (around 200°F).

Non-volatile condensables with these insulations will presumably not present any evaporation problems at temperatures below 200°F. But if the insulation, when heated or irradiated, releases volatile substances that can condense on colder surfaces, optical systems may be impaired by clouding or corroding.

Table 1

A Comparison of the Weight Loss of Teflon TFE, Specification 44*, and Novathene in a High Vacuum.

Material	Weight of wire sample (grams)	Temperature (°F)	Time in vacuum (hours)	Weight loss (percent)
Teflon TFE	2.0	212	100	0.04
Teflon TFE	N.A.†	300	168	0.29
Novathene	10.6	200	168	0.06
Novathene	10.7	250	168	0.11
Novathene	13.6	200	100	0.07
Specification 44*	0.7347	275	200	0.07

†Not available.

A series of simple experiments was undertaken to study the corrosive nature of evolved gases in a high vacuum. Three insulation materials were used: Teflon TFE, Specification 44*, and Novathene. Mirrors of vacuum-deposited copper and aluminum represented vulnerable optical parts and other components in a space vehicle. The mirrors were placed in glass ampoules to which were added one gram of insulation; these were sealed under a high vacuum of 10^{-6} Torr or less and irradiated with γ-rays. The mirrors were then examined for evidence of corrosion. Photomicrographs were taken within half an hour after the mirrors were removed from the ampoules, in order to minimize oxidation. Figures 1 and 2 show a series of typical photomicrographs. As a control, some of the mirrors were subjected only to vacuum and irradiation. The copper control mirror irradiated to 100 megarads is slightly pitted. These observations and some others (Reference 5) indicate a serious potential corrosion hazard with Teflon TFE but not with Specification 44* or Novathene (References 4 and 6).

RADIATION RESISTANCE

Organic materials, such as those discussed in this report, are susceptible to damage from nuclear radiation. The atoms in organic materials are held together by strong exchange forces arising from a mutual sharing of electrons. This sharing or bonding is termed a "covalent bond." Damage to organic materials is caused by ionization and excitation processes. The energy required to break a covalent bond is less than the energy required to ionize a molecule. When a molecule is ionized by radiation and recombines with an electron, an amount of energy equal to the ionization energy is released within the molecule and may break the bond. Bonds may also be broken when energy is absorbed by the excitation process. In either case, the end result is a chemical change; the molecules that give the material its identity are altered and new polymer chains are formed. The concentration of these degradation compounds increases with increasing radiation, resulting in changes in mechanical and physical properties. In most cases these changes are not beneficial, resulting in deterioration.

Plastic materials are susceptible to damage by all types of radiation because of the ease with which the molecular structure can be reoriented. Since plastics are polymers, the reorientation consists of the formation of new bonds between chains, the breaking of chains, the evolution of gases, and possible reaction with the environment.

An interesting phenomenon in the irradiation of many organic materials is cross-linking. Figure 3 shows this process as it occurs in polyethylene. The individual chains are actually thousands of atoms long; only a small part of the chain is shown here. When radiation impinges on the material, the energy is transferred to the polymer, breaking the C-H bond, which is weaker than the C-C bond. Hydrogen is emitted and the two carbon atoms cross-link to form a larger radical.

Figure 4 shows the effect of cross-linking on a more macroscopic scale. The three horizontal lines represent long chains of C-C bonds. The X's indicate where the breaking of C-C bonds (scission) occurs, and the vertical lines represent the cross-linking between chains. A

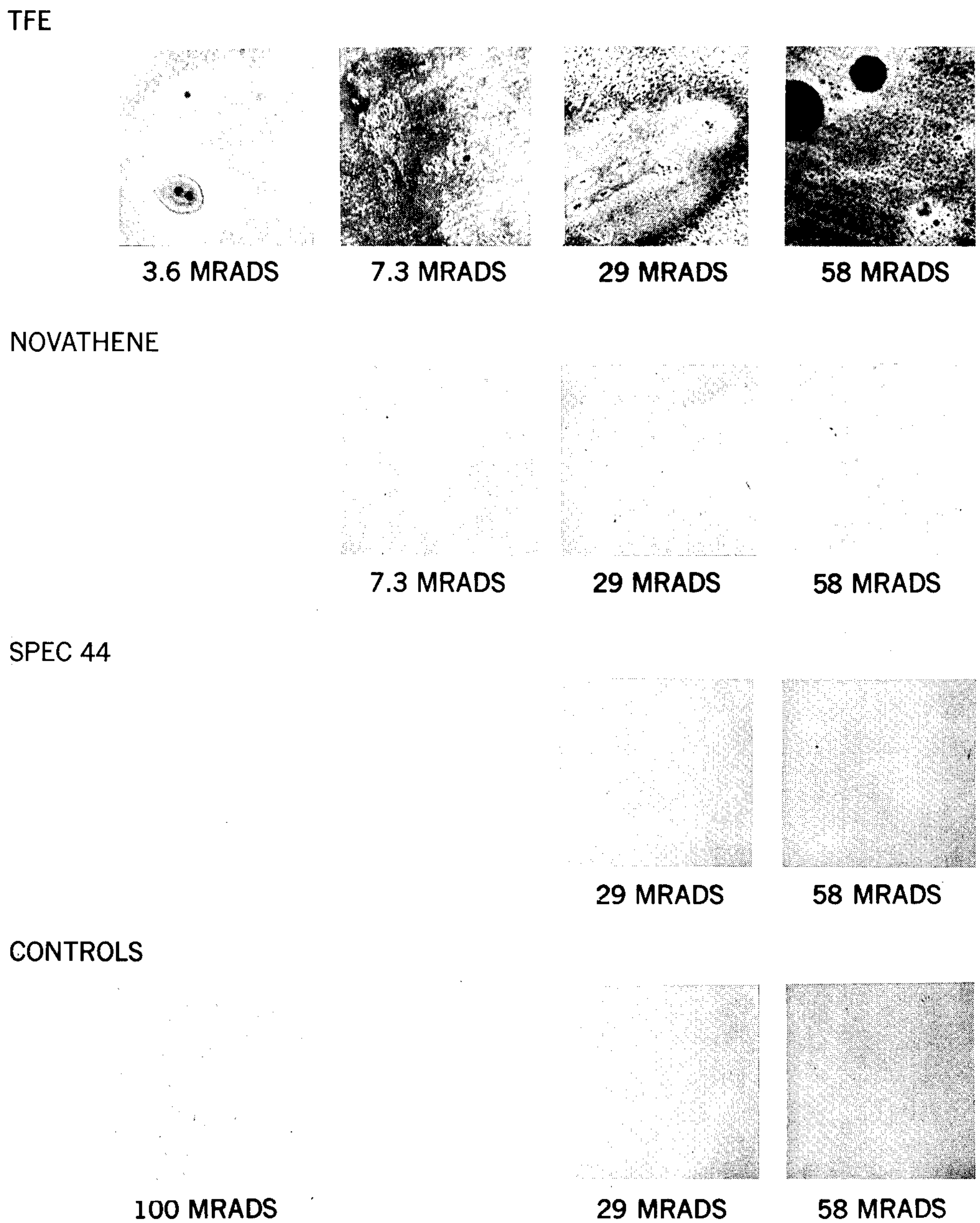

Figure 1—Photomicrographs of copper mirrors exposed to irradiated Teflon TFE, Novathene, and Specification 44*, in vacuum.

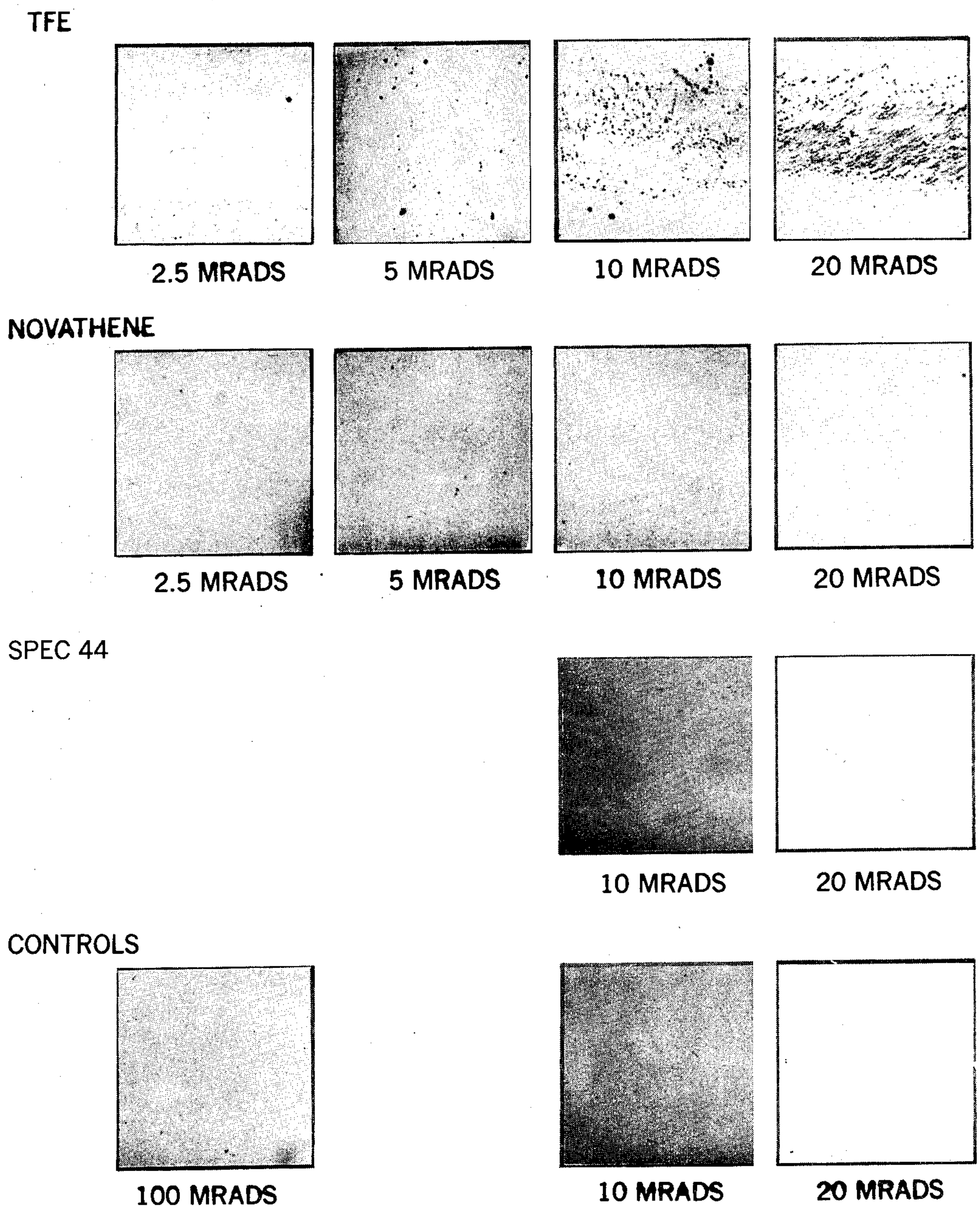

Figure 2—Photomicrographs of aluminum mirrors exposed to irradiated Teflon TFE, Novathene, and Specification 44*, in vacuum.

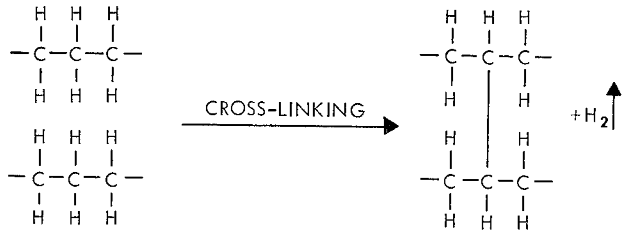

Figure 3—Cross-linking in polyethylene.

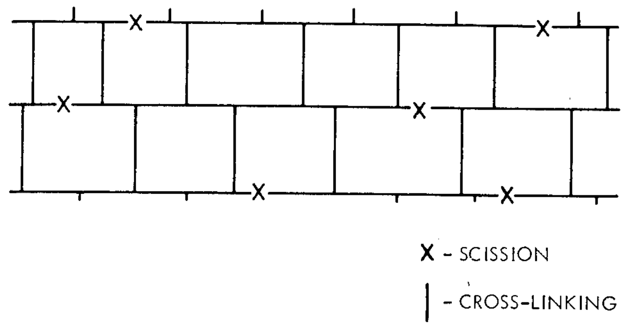

Figure 4—Effects of cross-linking and scission on a macroscopic scale.

material that cross-links strongly increases in strength with irradiation up to a certain point, after which the material begins to degrade. A material like Teflon, which has a stronger C-F than C-C bond, would probably undergo more scission than cross-linkage, resulting in a degradation with irradiation (Reference 2).

Different levels of ionizing irradiation are encountered in different regions of space. The four main sources of radiation in space are the inner radiation belt, the outer radiation belt, solar emission, and cosmic rays. Table 2 shows the ionization doses produced by the protons and electrons at the peak of the inner radiation belt, by the electrons at the peak of the outer radiation belt, by protons and electrons of the steady solar emission, and by cosmic-ray protons (Reference 1).

The radiation resistance of polyethylene is approximately three orders of magnitude greater than that of Teflon. A special non-volatile antirad system incorporated into the Novathene insulation increases the dose of ionizing radiation the insulation can withstand. Specification 44*, Novathene, and Rayolin-N* insulation materials have successfully withstood doses of 500 megarads in air with no deterioration of electrical properties and very little change in physical properties.

When Teflon TFE is irradiated in air, the polymer is quickly degraded and becomes useless when it has absorbed one or two megarads. If Teflon TFE is irradiated in a high vacuum, it is degraded more slowly; it loses 88 percent of its original elongation at a dose of 8 megarads.

Irradiated polymers, almost without exception, release gaseous substances that may corrode spacecraft components. Irradiated polyolefins principally release hydrogen, and small amounts

Table 2

Ionization Dosages in Space Produced by Atomic Particles.

Radiation	Ionization (megarads/year)	
	Surface and through 1 mg/cm^2	Through 1 g/cm^2
Inner radiation belt	10^6	10^{-1} - 1
Outer radiation belt	10^5 - 10^7	10^{-2} - 1
Solar emission	10^{-1} - 10	10^{-4} - 10^{-3}
Cosmic rays	10^{-6} - 10^{-5}	10^{-6} - 10^{-5}

of low molecular weight hydrocarbons such as methane. Scavengers, as well as stabilizers, have been included in the formulation of the polyvinylidene fluoride jacket for the Specification 44* insulation; they effectively inhibit the release of any undesirable gaseous products, as can be seen from the results of the vacuum irradiation tests shown in Figures 1 and 2. Tests have shown that irradiated Teflon releases a corrosive fluorine gas (Reference 4).

WEIGHT

Weight is a prime factor when considering an insulation material for use in spacecraft. For example, if a highly elliptical orbit with an apogee of 20,000 nautical miles is desired, an increase of only 2 pounds in weight could result in an apogee 1,000 nautical miles less than desired. The weight penalty is greater for greater apogees. Table 3 compares the weights of the insulation materials discussed in this report.

Table 3

Weight Comparison of Insulations.

Insulation	Wire Size (AWG)	Stranding	Voltage Rating (v)	Weight (lb/1000 ft)	Outside Diameter
Specification 44*	28	7/36	600	0.90	0.029
Novathene	28	7/36	600	0.89	0.033
Rayolin-N*	28	7/36	600	0.89	0.033
Teflon TFE	28	7/36	600	1.30	0.039
Teflon FEP	28	7/36	600	1.30	0.039
Specification 44*	24	19/36	600	1.90	0.039
Novathene	24	19/36	600	2.10	0.045
Rayolin-N*	24	19/36	600	2.10	0.045
Teflon TFE	24	19/36	600	2.43	0.048
Teflon FEP	24	19/36	600	2.43	0.048
Specification 44*	20	19/32	600	4.30	0.054
Novathene	20	19/32	600	4.60	0.059
Rayolin-N*	20	19/32	600	4.60	0.057
Teflon TFE	20	19/32	600	5.05	0.062
Teflon FEP	20	19/32	600	5.05	0.062

RESISTANCE TO COLD FLOW, CUT-THROUGH, AND ABRASION

The cold flow, cut-through, and abrasion resistance characteristics of an insulation material are important measures of its workability and the amount of fabrication deterioration that wires and cables using it can withstand. Wires to be used in satellite harnesses should have good cold flow, cut-through, and abrasion resistance to guard against damage caused by lacing, clamping, and vibration.

Resistance to Cold Flow

Samples of Novathene, Rayolin-N*, Teflon TFE, Specification 44*, and Teflon FEP insulated wires were tested for cold-flow resistance. The test specimens consisted of twelve inches of previously untested wire, from which one-half inch of insulation had been removed at one end. The specimens were placed in the test fixture (Figure 5) with the axis of the specimen perpendicular to the deformation bar (an inverted V with a 90-degree angle and a 0.005-inch radius). The stripped ends of the specimen were connected to an automatic timing circuit so that contact of the deformation bar with the conductor of the specimen would stop an elapsed-time indicator, thus indicating a failure. The load on the deformation bar was selected so as to cause an instantaneous failure, and was then reduced by 0.63 pound for each subsequent test. The specimen was advanced 1 inch for each new test, and the time of failure was recorded for each load. Table 4 shows the results of this test (References 7 and 8).

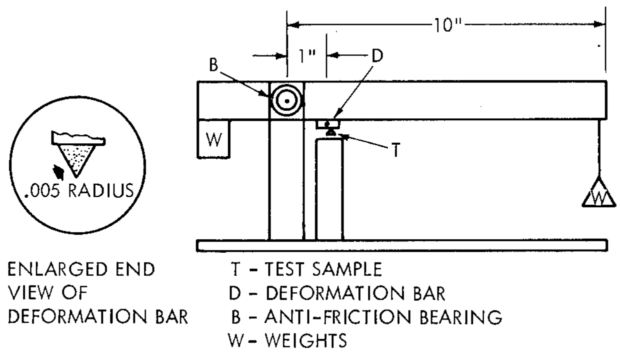

Figure 5—Load deformation tester.

Table 4

Comparative Cold Flow Resistance.

Load (pounds)	Time to Failure (hours: minutes: seconds)				
	Novathene	Rayolin-N*	Teflon TFE	Spec. 44*	Teflon FEP
13.13	00:00:01	--------	--------	--------	--------
12.50	00:00:03	--------	--------	--------	--------
11.88	00:00:03	--------	--------	--------	--------
11.25	00:00:08	00:00:04	--------	--------	--------
10.62	00:01:24	00:00:24	00:00:02	--------	--------
10.00	00:04:33	00:00:40	00:00:03	--------	--------
9.36	00:22:17	00:07:05	00:00:03	--------	--------
8.75	01:12:27	00:30:12	00:00:17	00:00:02	--------
8.12	07:32:06	00:49:00	00:01:53	00:00:22	--------
7.50	19:55:00	04:38:18	00:09:52	00:08:30	--------
6.88	>24:00:00	19:23:33	01:13:29	00:50:00	--------
6.25	--------	>24:00:00	15:31:10	08:00:00	00:00:02
5.62	--------	--------	>24:00:00	>24:00:00	00:00:03
5.00	--------	--------	--------	--------	00:00:44
4.37	--------	--------	--------	--------	01:14:07
3.75	--------	--------	--------	--------	>24:00:00

Resistance to Cut-Through

Samples of Novathene, Specification 44*, Rayolin-N*, Teflon TFE, and Teflon FEP insulated wires were tested for resistance to cut-through. The test specimens consisted of twelve inches of previously untested wire from which the insulation was removed for one-half inch at one end. The specimens were placed in the test fixture (Figure 6) with the axis of the specimen perpendicular to the knife edge (an inverted V with a 90-degree angle and a 0.005-inch radius). A signal light was attached to the stripped end of the specimen to indicate cut-through. The light went on when the knife edge cut through the insulation and made contact with the conductor. An arbitrary knife-edge closure rate of 0.20 inch per minute was used on all specimens so that *all* of the results would be comparable. The specimen was rotated through 90 degrees and advanced approximately 2 inches after each measurement. The total force in pounds on the knife edge at the time of failure was recorded; Table 5 and Figure 7 show the results (References 7 and 8).

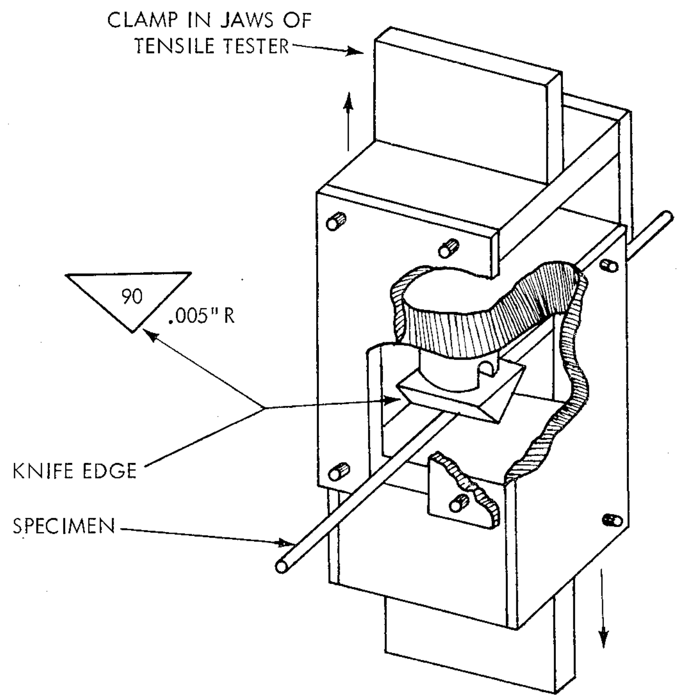

Figure 6—INSTRON cut-through test jig.

Table 5

Comparative Cut-Through Resistance.

Insulation material	Cut-through force (pounds)				
	Test 1	Test 2	Test 3	Test 4	Average
Novathene	14.3	12.2	12.96	12.5	13.07
Specification 44*	11.5	12.8	11.2	13.3	12.2
Rayolin-N*	12.1	12.4	12.1	11.7	12.1
Teflon TFE	9.2	9.6	9.2	9.1	9.3
Teflon FEP	7.0	6.5	6.7	6.5	6.7

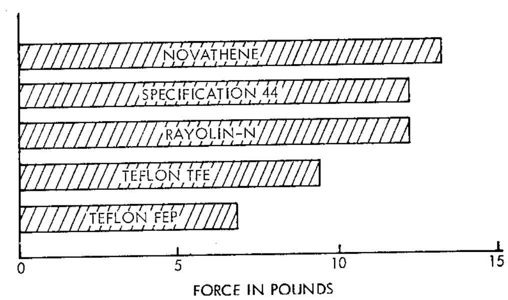

Figure 7—Cut-through resistance (average of four readings).

Resistance to Abrasion

Samples of Novathene, Specification 44*, Rayolin-N*, Teflon TFE, and Teflon FEP insulated wires were tested for abrasion resistance in strict accordance with the procedures given in MIL-T-5438. The object of this test was to determine how many inches of a standard abrasive tape under a constant specified force could be pulled past the wire specimen before contact was made between the tape and the center conductor of the wire (Figure 8). Each specimen received eight

abrasion tests, being moved forward 2 inches and rotated through 90 degrees between tests. Abrasion resistance is defined as the arithmetic mean of all readings below the arithmetic mean of all eight readings. Table 6 and Figure 9 show the results (References 7 and 8).

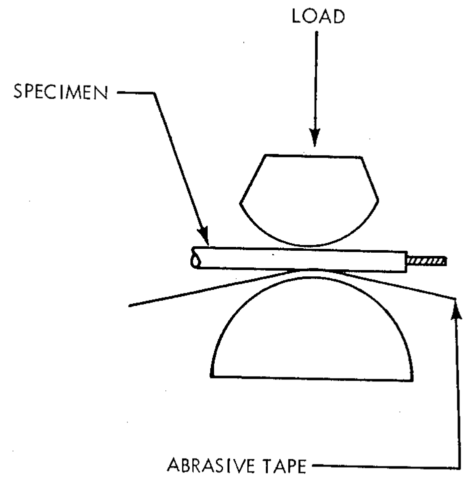

Figure 8—Abrasion resistance tester.

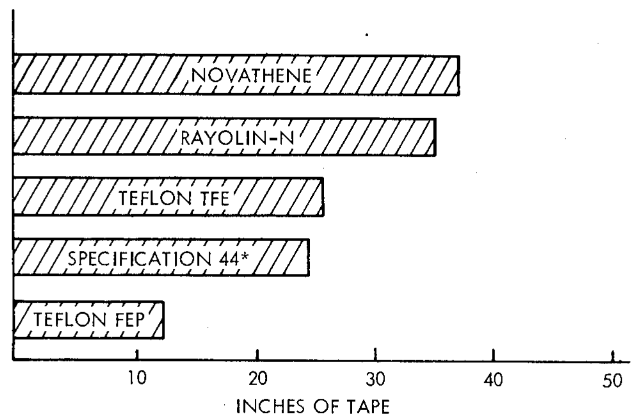

Figure 9—Abrasion resistance.

Table 6

Comparative Abrasion Resistance.

Abrasion readings	Inches of tape				
	Novathene	Rayolin-N*	Teflon TFE	Spec. 44*	Teflon FEP
1	40.4	36.7	25.1	24.5	12.3
2	43.0	39.5	21.7	24.3	15.3
3	36.7	45.9	27.5	24.5	15.2
4	33.8	39.8	30.8	24.4	12.3
5	36.9	33.6	33.4	24.4	12.2
6	36.7	39.5	30.5	24.4	18.5
7	49.0	33.7	27.4	27.0	15.2
8	37.5	45.9	30.5	24.1	12.3
Arithmetic average	39.4	39.3	28.4	24.7	14.2
Abrasion resistance	36.3	34.7	25.4	24.3	12.3

ADHESION TO POTTING COMPOUNDS

Potential sources of trouble in spacecraft are: fatigue of soldered joints, breakage of wire at solder joints in connector assemblies, and penetration into the back of the connector by moisture, dirt, dust, and other foreign matter. Mechanical clamps give some protection at the cost of

bulkiness but offer nothing in terms of electrical performance. For these reasons, the ends of the wire in the contacts at the back of the connector are generally potted. The potting materials seal out foreign matter, immobilize the solder joint, and hold the wire, provided that there is a good bond between the potting material and the wire insulation.

Teflon surfaces are notoriously difficult to bond. The Teflon insulation will most probably break away from potting compounds, especially under vibration or handling; Teflon-insulated wires are often held in the potting compound only by the soldered connection and the shrinkage of the potting compound around the insulation (Reference 9). The bonding strength of Teflon can be enhanced by etching the surface of the insulation with a sodium-naphthalene solution; the strength of the bond depends on the depth of the etch (Reference 10). This procedure requires the use of a vented hood and glass containers, and adds an extra step in the fabrication of a wire harness.

Specification 44*, Novathene, and Rayolin-N* insulations, on the other hand, adhere very well to potting compounds without special preparation; and these insulations normally have greater bonding strength than etched Teflon (Reference 11).

RESISTANCE TO WICKING DURING SOLDERING

Flow of solder under the wire insulation should be kept to a minimum. Excessive wicking (more than one-eighth inch) adds useless weight and promotes stiff joints. Most important, it causes the copper conductor to break under bending or vibration. It also makes it difficult to fabricate a cable harness in limited space. Since the harness is laced up to the connection for mechanical support, the wires must be able to take stresses at some point other than the solder connection, which is the weakest point of the harness (if the solder wicks too far under the insulation, all stresses are transmitted to the solder connection).

The major factor determining the amount of wicking is the outer coating of the copper conductor itself. The conductors most often used in hook-up wire are silver-plated and tinned copper. Solder wets better on silver than on tin; thus, the wicking action is greater on silver-plated than on tinned copper (see Figure 10). Tinned copper conductors can be used with all the insulations discussed in this report except Teflon TFE, which must be extruded on the conductor and then heated at high temperatures. The temperature used in processing Teflon TFE is above the melting point of tin but below that of silver. Therefore, Teflon TFE insulation cannot be applied to tinned copper; silver-plated copper must be used, and this results in increased wicking.

TEMPERATURE CHARACTERISTICS

The maximum recommended continuous duty service temperatures for the insulation materials discussed in this report are:

Novathene	125°C
Specification 44*	135°C
Rayolin-N*	135°C
Teflon TFE	260°C
Teflon FEP	205°C

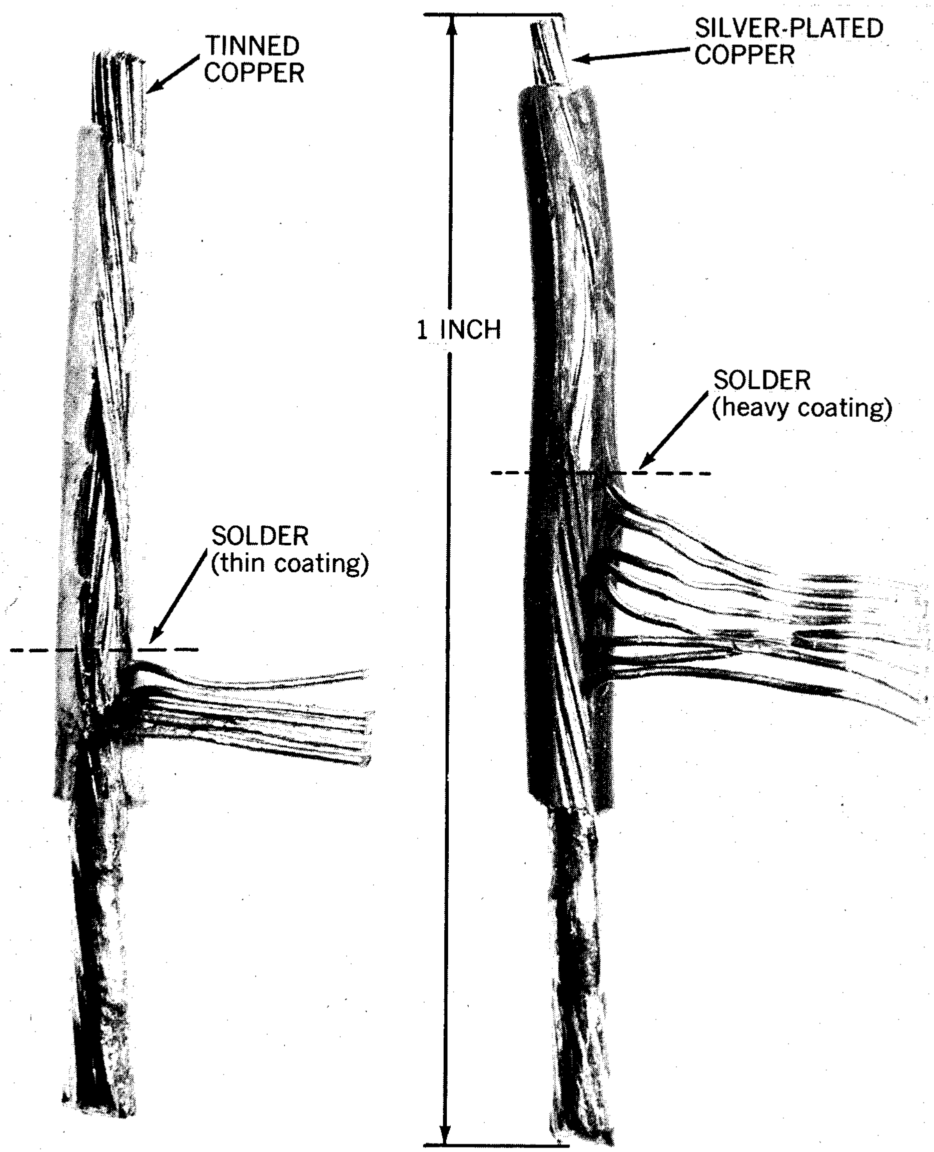

Figure 10—Comparison of wicking action on tinned-copper and silver-plated-copper conductors.

When fabricating a cable harness, it is customary to use miniature series connectors with high-density contacts, for reasons of size and weight. This means soldering in close quarters, where the soldering iron can very easily come in contact with the insulation material. Teflon TFE, Specification 44*, Rayolin-N*, and Novathene can withstand contact with a hot soldering iron for reasonably long periods without the least danger of melting the insulation and causing short circuits or impairing reliability. On the other hand, Teflon FEP is destroyed by momentary contact with a hot soldering iron (Reference 12).

CONCLUSIONS

This report compares the results of some tests on insulation materials as a guide in selecting wire insulations for spacecraft. The materials discussed have been flown successfully in unmanned scientific satellites. Factors that must be considered when choosing a material (orbit, expected temperature environment, presence and/or location of optical equipment, weight and/or space limitations) will depend on the particular spacecraft.

ACKNOWLEDGMENTS

I wish to thank Dr. Henry E. Frankel, Mr. Aaron Fisher, Mr. David F. Butcher, and Mr. Robert G. Martin for their assistance in collecting and evaluating the material discussed in this report.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, September 26, 1967
722-861-31-75-01

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